INSTRUMENTS AND METHODS USED IN RADIOMETRY, III

THE PHOTO-ELECTRIC CELL AND OTHER SELECTIVE RADIOMETERS

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CONTENTS

I. INTRODUCTORY STATEMENT

During the past 10 years investigations have been in progress in this Bureau to determine the characteristics, comparative sensitivity, and applicability of various types of instruments for measuring radiant energy.

The various types of instruments which may be used for measuring radiant energy may be divided into three groups.

Group 1 consists of radiometers which are quite nonselective in their response to stimuli of radiant energy of all wave lengths yet measured, extending from the extreme ultra-violet (Schumann region $\lambda = 0.1\mu$) to the longest infra-red rays yet isolated, viz, $\lambda = 340\mu$ ($\mu = 0.001$ mm).

In these instruments the radiant energy is absorbed by a blackened receiver and converted into heat.

To this group of radiation meters belong (1) the Nichols radiometer, which functions as the result of gas repulsion against a blackened vane, which is suspended in a partial vacuum and exposed to radiation; (2) the thermocouple (and auxiliary galvanometer) and the Boys radiomicrometer (which consists of a thermocouple attached to the suspended coil of a d'Arsonval galvanometer), which function as the result of generation of an electric current by heating the juncture of the two metals by absorption of radiant energy; and (3) the Langley bolometer, which functions as a result of a change in electrical resistance of a very thin, blackened strip of metal, caused by the heat produced by absorbing radiant energy, to which it is exposed in the form of an arm of a Wheatstone bridge.

This group includes also calorimetric devices. Other devices such as expansion of a gas or metal due to warming by absorption of radiant energy are not sufficiently sensitive to be considered.

There is no marked difference in the limiting sensitivity of these instruments. It is primarily a question of adaptability and speed. If it requires two seconds to obtain a galvanometer reading when using a bolometer, it will require three to four seconds when using a thermopile and one to two minutes, or even as high as five minutes, when using a Nichols radiometer.

By marked difference in sensitivity is meant a factor of 10 to 100. The factor, 2, counts but little when we are interested in measuring the radiations from an eighth to tenth magnitude star, or the light reflected from one of Jupiter's satellites.

In previous communications attention was directed principally to these nonselective instruments—that is, instruments which function independently of the (frequency) wave length of the stimulus—because they have a wider application than instruments which respond only to certain frequencies, whether "visible" or "ultra-violet" radiations.

Group II includes substances which have the property of decreasing in electrical resistance when exposed to radiant energy of short wave lengths, especially the visible and ultra-violet rays. The character of this phenomenon depends entirely upon the wave length (frequency) of the radiant energy stimulus. It does not depend upon thermal conditions; that is, it does not depend upon the amount of radiant energy absorbed and the consequent rise in temperature of the substance exposed to radiation. In fact,

at least some of these substances undergo the greatest change in resistance (are the most sensitive) for radiations of wave lengths which are the least absorbed. The resistance of selenium increases with decrease in temperature, which is opposite to the effect produced by "light" rays. For example, experiments show that a selenium cell having a resistance of 1 000 000 ohms at 20° C increases to three times that value (3 000 000 ohms) at 0° C. When such a cell was exposed to diffuse daylight, its resistances decreased to one-tenth to one-fiftieth of its value when unexposed to light.

Many substances are "light sensitive," for example, copper oxide, sulphides of antimony, silver, etc. The best-known example is crystalline selenium, which will be discussed presently.

Group III includes substances which, when charged to a negative potential (in an evacuated chamber), lose their charge when exposed to light, especially violet and ultra-violet rays. When used in this manner they are commonly called "photoelectric cells." The emission of electrons is a surface phenomenon which is easily affected by oxidation of the surface.

The effect produced by exposing the electrode to light does not disappear instantaneously. It is claimed that if light is applied to the cell without a potential difference, and the light is then interrupted and the field is applied, there is found a considerable photoelectric current.

The photoelectric cell seems to become fatigued and, unless it is of special construction, its response is not directly proportional to the intensity of the stimulus; but differing from the selenium cell, the writer has not found this lack of proportionality of response to depend upon the wave length of the exciting light.[1]

Many substances (not necessarily metal) are sensitive photoelectrically. Silver iodide is said to be ten times as sensitive as pure aluminum.

The sensitivity of potassium is increased one hundred times by changing the material into a hydride.

For the alkali metals the wave length of maximum sensitivity shifts to the long wave lengths with increase in molecular weight; for Na, $\lambda_m = 0.4\mu$; for K, $\lambda_m = 0.436\mu$; for Rb, $\lambda_m = 0.5\mu$.[2] In the nonselective radiometers the high local sensitivity of the

[1] In one of the tests on a photoelectric cell of potassium it was found that on doubling the intensity of the light the correction for lack of proportionality of response (galvanometer deflection) was 10 per cent, while for an increase in intensity of ten times the original value this correction was 15.3 per cent.

[2] Ladenburg, Ann. der Phys. (4), 12, p. 558; 1903. For a complete summary, see Chr. Ries, Das Licht in Seiner Elektrischen und Magnetischer Wirkungen, Leipzig, 1909.

selective instruments seems to be spread over the whole spectrum, with a corresponding reduction to a uniform and much lower value.

In previous communications [3] the characteristics and comparative sensitiveness of the various types of nonselective radiometers (Group I) were described.

In the first communication [4] attention was called to the fact that, at that time, but little was known concerning the selective radiometers, and that their application was very limited. In the meantime extensive researches by various observers have thoroughly proven that the selenium cell, in spite of its very high sensitivity, is useless as an instrument for precise measurements.

On the other hand, the photoelectric cell, Group III, is being developed into a precision instrument which will be useful for special kinds of measurements in the region of the spectrum extending from the yellow throughout the extreme ultra-violet. In view of the fact, as will be shown presently, that in the violet and ultra-violet, a photoelectric cell of potassium hydride is more sensitive than a thermopile, it can be used to supplement the latter in certain radiometric investigations; for example, in transmission and reflection measurements.

There seems to be considerable misconception concerning the functioning of selective and nonselective radiometers. Hence, before discussing the various types of selective radiometers in detail, it is relevant to add a few comments on the physical conditions which control the selectivity and nonselectivity, also the proportionality of the response, when the radiometer is irradiated [5] by radiant energy of different wave lengths.

A radiometer, giving responses which are directly proportional to the incident radiation is not necessarily equally sensitive to all wave lengths.[6] The thermopile is a typical example. The surface of the receiver is equally sensitive to all wave lengths because it is covered with lampblack, which has the property of absorbing equally (within experimental errors of observation) all wave lengths. If the thermopile receiver were covered with chromium oxide, it would absorb 97 per cent in the visible spectrum and 85

[3] Instruments and Methods, I, this Bulletin, **4**, p. 392, 1908; Instruments and Methods, II, this Bulletin, **9**, p. 7, 1911; Various Modifications of Thermopiles, this Bulletin, **11**, p. 132, 1914; and Energy Measurements in Absolute Value, this Bulletin, **12**, p. 504, 1916.

[4] This Bulletin, **4**, p. 454, 1908; **9**, p. 45, 1912.

[5] It is logical to use the term "irradiate" instead of "illuminate" in view of the fact that both visible and invisible radiant power is being discussed. For a logical use of the term "irradiate" in connection with X rays and crystal structure, see a paper by W. H. Bragg, Phil. Mag., **27**, p. 885; 1914.

[6] In a recent paper on radiometric apparatus for use in psychological optics (Ferree and Rand, Psychological Monograph No. 103, p. 1, Princeton University Press) the statement is made that an instrument giving direct proportionality of response is equally sensitive to all wave lengths.

to 95 per cent, depending upon the wave length, in the infra-red.[7] If the surface of the receiver were covered with aluminum oxide, it would absorb only 15 per cent in the visible spectrum, while at 8.8μ it would be as "black" as lampblack, absorbing 98 per cent of the incident radiation. Evidently the question of equality of sensitivity for different wave lengths depends entirely on the kind of material used as an absorbing surface of the thermopile (or bolometer) receiver.

The response of the thermopile is directly proportional to the intensity of the incident radiation because, for the small rise in temperature involved, the thermal emf generated is directly proportional to the heat generated, which in turn is directly proportional to the energy absorbed. However, in order to utilize this direct proportionality of response of the thermocouple it is necessary to design the galvanometer so that its deflection is directly proportional to the current passing through the circuit.

On the other hand, the distinguishing characteristics of the photoelectric cell is its selective sensitivity to various wave lengths, being the most sensitive to the ultra-violet. Thus far it has not been possible to modify appreciably this inequality of sensitivity for different parts of the spectrum. However, while most photoelectric cells do not give responses which are directly proportional to the intensity of the incident radiation, it is possible to design the cell so that it gives direct proportionality of response.

In concluding this part of the discussion of selective radiometers it is relevant to add that the eye is one of the most sensitive detectors of radiant energy. The unaided eye can detect a seventh to eighth magnitude star. It required a 3-foot reflecting telescope to detect a seventh-magnitude star by means of its total radiation. On the basis of the "light" emitted from a star, assuming a luminous efficiency of 20 per cent, it would require a 7-foot telescope combined with a stellar thermocouple in order to attain the sensitivity of the human eye. Calculations show that the eye responds to light having an intensity less than 1×10^{-9} erg—a value so small that it would require 60 million years to raise 1 g of water 1° C. Since the thermocouple (or bolometer) is nonselective, it gives an accurate register of the radiation from an incandescent body; as, for example, a star. The stars that appear the brightest to the eye do not necessarily appear the "brightest" radiometrically, because they may have dark companions. In fact, a very useful application of the thermocouple will be a search

[7] This Bulletin, 9, p. 283; 1913.

for binary stars having companion stars which are not sufficiently luminous to be visible to the eye.

II. THE PHOTOELECTRIC CELL

Recent advances in the construction of photoelectric cells, especially the highly sensitive cells of Kunz, in which the active material is potasssium hydride, seem to warrant their use as a precision radiometer for a limited class of investigations, such as, for example, transmission and reflection spectra in that part of the spectrum extending from the yellowish green into the extreme ultra-violet. Such investigations have already been made.[8] In stellar photometry important results have been obtained by Stebbins [9] in the measurement of the variation in brightness of variable stars, while numerous other applications are being made. However, before undertaking such applications the cell must be thoroughly tested for direct proportionality between the intensity of the incident light and the resulting photoelectric current. This

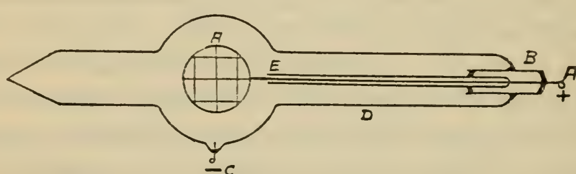

Fig. 1.—*Photoelectric cell (Kunz)*

may be accomplished by changing the distance of the light, by using Nicol prisms, or by means of a sectored disk, as described elsewhere in this paper.

In stellar radiometry its greatest usefulness will be in studying variable stars which do not change in color.

(*a*) *Description of Cell.*—Various designs of photoelectric cells have been suggested. Kunz [10] has described the latest developments which appear to give a cell which is quite free from "dark currents"; that is, leakage currents flowing when the cell is not exposed to light. The design is illustrated in Fig. 1. It may be constructed of quartz or of glass or of glass with a quartz window. The central bulb is about 3.5 cm in diameter. The cathode, *C*, is of small platinum wire, and this part of the bulb is silvered to

[8] Hulburt, Astrophys. Jour., 42, p. 205, 1915; and Nathanson, Phys. Rev., 7, p. 403, 1916.
It is beyond the scope of this paper to give a complete history of the development of the photoelectric cell. The recent developments are easily accessible, and the early work is described by Ries, "Das Licht in Seiner Elektrischen Und Magnetichen Wirkungen," Leipzig, 1909.

[9] Stebbins, Bull. Lick Observatory, 8, pp. 186 and 192; 1916.

[10] Kunz, Phys. Rev., 7, p. 62, 1916; Astrophys. Jour., 45, p. 69, 1917.

insure good contact with the platinum and the glass. The anode, *A*, is a ring of platinum about 2 cm in diameter. Fine silver or platinum wire is stretched across this ring, thus forming a net which produces a more uniform electric field. The anode is surrounded by a long glass tube to prevent leakage. The use of a special nonconducting glass for this part of the tube has been suggested. It appears feasible to make the supporting tube, *E*, of quartz (attaching it to the glass by means of the glass fluxes now obtainable), which would reduce the leakage over the inner surface. For the most refined work in stellar photometry, and for measuring weak radiations, the anode, *A*, is surrounded by a platinum cylinder, *B*, by means of which the surface and the electrolytic currents are lead to earth. The dark currents may be further suppressed by wrapping tin foil around the cylindrical part, *D*, and the cathode, *C*; and it can be compensated by the application of a lower potential [11] at the platinum cylinder, *B*, as described elsewhere in this paper.

(*b*) *Preparation of Cell.*—The manner of construction of a photoelectric cell is intricate, and readers are referred to original sources for details.[12] The cells most commonly used are made of potassium hydride or of pure sodium.

In order to produce good contact [13] at the cathode a layer of silver is deposited on and around the platinum terminals on the inside of the bulb, and the potassium is distilled upon the silver which is kept cool by ice or cold water. The cylindrical part of the tube, *D*, Fig. 1, is heated (160° to 240° C, according to the alkali metal used), by means of a heating coil while the distillation is in progress. Hydrogen is introduced by heating a strip of palladium in a side tube. The potassium hydride is formed (by Schulz, loc. cit.) by applying a potential of about 550 volts direct current to the cell (Kunz, loc. cit., mentions 280 volts for rubidium), the potassium electrode being negative, with about 3000 ohms resistance in series with the cell. On closing the circuit for a few seconds the potassium assumes a brilliant violet-blue color. The circuit is then broken and the hydrogen pumped out. Helium or argon, free from oxygen, is then introduced, the pressure being regulated to give the maximum galvanometer deflection when the cell is exposed to light.

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[11] Nathanson, Astrophys. Jour., **44**, p. 137; 1916.

[12] The pioneers in this work are Elster and Geitel, Ann. der Physik, **43**, p. 225, 1891; **48**, pp. 338 and 625, 1893; Phys. ZS., **10**, p. 457, 1909; **11**, pp. 257 and 1082, 1910; **13**, p. 468, 1912 (formation of hydride of alkali metals); **14**, p. 741, 1913.

[13] Schulz, Astrophys. Jour., **38**, p. 187; 1913. Instead of the platinum cylinder, *B*, Fig. 1, a coating of silver, touching a sealed-in platinum wire, is used; Astrophys. Jour., **46**, p. 241; 1917.

The successful distillation of the alkali metal, for example, potassium) into the bulb has been described by Ives [14] and by Hulburt,[15] who prepared sodium cells.

The preparation of cells of caesium and rubidium from the chlorides of these metals has been described by Cornelius.[16]

The conditions controlling the sensitivity of the photoelectric cells with alkali metals in hydrogen have been investigated by Kemp.[17] He varied the conditions as regards gas pressure, electrode distance, potential difference applied to the electrodes, area illuminated, intensity of illumination, and temperature of the cell. Kemp found that the sensitivity was increased more than 100 times by formation of the hydride. The sensitivity did not appear to vary much with temperature. For hydrogen he found a pressure of 2 to 3 mm. of mercury to produce the highest sensitivity, the optimum electrode distance being 5 to 6 mm.

One objectionable characteristic of a photoelectric cell is its lack of direct proportionality of response (photoelectric current) with variation in intensity of illumination. Conflicting reports have been published; some experimenters having cells which gave direct proportionality while others did not find proportionality of response.

Kunz [18] seems to have overcome this difficulty to some extent, and seems to be able to make cells which are quite reproducible in their characteristics. This is accomplished by distilling the potassium over the whole bulb, except a small opening 5 to 8 mm. in diameter, for admitting radiation into the bulb. A further improvement is in producing a more uniform electric field by using a net of wire instead of the single loop of platinum previously used. In this manner he is able to operate a spherical form of cell so that, for low illuminations, it gives exact proportionality of photoelectric current for a variation of 4 to perhaps 10 times the intensity of illumination. Using a cylindrical cell, with parallel electrodes, the current was found to be proportional to the illumination, for a variation of 100 times in intensity if the cell was filled with argon.

Recently he has described expriments on amplification of the photoelectric current by means of the audion amplifier.[19]

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[14] Ives, Astrophys. Jour., 39, p. 428; 1914.

[15] Hulburt, Astrophys. Jour., 41, p. 400; 1915.

[16] Cornelius, Phys. Rev., 1, p. 16: 1913.

[17] Kemp, Phys. Rev. (2), 1, p. 274; 1913. See also paper by Ives, Astrophys. Jour., 39, p. 428: 1914.

[18] Kunz, Astrophys. Jour., 45, p. 69; 1917.

[19] Kunz, Phys. Rev. (2), 10, p. 205; 1917.

An outstanding difficulty that needs investigation is the variation (decrease) in sensitivity with age. While this does not appear to be serious, it is nevertheless important to determine whether it is due to release of gases from the walls of the cell, and whether the cell can be aged at the time of construction.

(*c*) *Voltage-Current Characteristics.*—It has just been noticed that the sensitivity of a photoelectric cell is a complicated function of gas pressure, electrode distance, etc. Under the present caption it is of interest to describe the electrical characteristics of the cell.

Applying a potential difference to the electrodes of an unilluminated photoelectric cell it is found that the voltage can be increased to a certain definite maximum value before ionization occurs. If this voltage is exceeded by an amount which is barely perceptible on a voltmeter, a deflection of the galvanometer results, indicating a flow of current through the cell. This is the critical voltage (and critical current) above which the cell can not be operated without introducing a permanent galvanometer deflection. This is to be avoided, as is also the "dark current" which is due to leakage over the cell. This leakage can be annulled as described under "Methods of operation."

Photoelectric cells, which are purchased, should be accompanied by a statement concerning the maximum voltage that can be applied. Even then the cell should be operated with caution. For example, a certain cell which was labeled "maximum 150 volts" could not be operated above 80 to 90 volts on account of excessive leakage. It would be of interest to determine whether this unstable condition varies with the age of the cell.

(*d*) *Voltage-Radiation Sensitivity.*—The variation of the radiation sensitivity of a potassium-hydride photoelectric cell with the voltage applied to the electrodes is shown in Fig. 2. In making this test the cell was exposed to light from a monochromatic illuminator. The intensity of the light was kept constant while the voltage which was applied to the cell was varied. The critical voltage of this cell was about 230 volts. It is of interest to note the rapid change in radiation sensitivity near the critical voltage. Hence, if high sensitivity is not required, it is advisable to use a lower voltage since the effects of a slight variation in voltage will be less perceptible at a lower voltage.

(*e*) *Spectral-Radiation Sensitivity.*—The highly selective character of the spectral-radiation sensitivity (the wave-length

sensitivity) of the photoelectric cell is shown in Fig. 3, which gives the apparent distribution of energy in the visible spectrum of a gas-filled tungsten lamp as observed, curve *A*, with a photoelectric cell, and the true energy distribution as observed, curve *B*, with a thermopile which is a nonselective radiometer. An ironclad Thomson galvanometer was used with both of these instruments.

From these curves it will be noticed that the photoelectric cell is not sensitive to the deep red. In the blue it is very sensitive, so that as a radiometer in this region of the spectrum it surpasses the thermopile or bolometer in sensitivity. Curve *C* gives the true sensitivity of the photoelectric cell of potassium hydride resulting from stimulating the cell with equal energies throughout the spectrum. It is the ratio of curve *A* to curve *B*, in view of

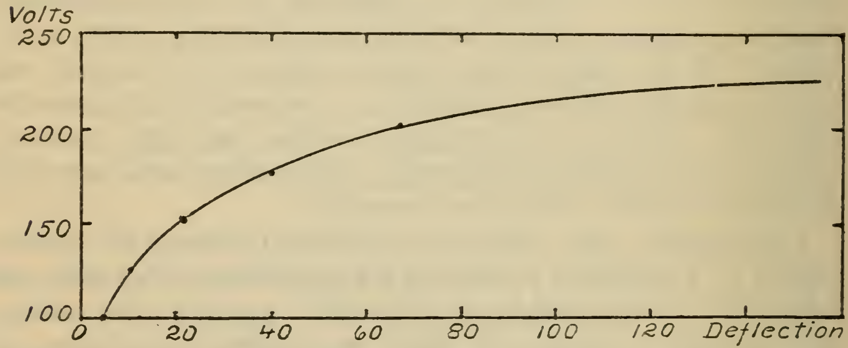

Fig. 2.—*Variation in radiation sensitivity of a photoelectric cell with change in applied voltage*

the fact that for this range of intensities the photoelectric current is proportional to the energy stimulus; or it is the wave-length sensitivity curve.

As already mentioned, the maximum sensitivity shifts toward the short wave lengths with decrease in atomic weight of the alkali metal. The data published by Ives [20] show a great variation in the wave-length sensitivity curves of potassium cells. In Fig. 4, curve *A* is shown the wave length, photoelectric sensitivity of calcium [21] and curve *B* of rubidium,[22] which has its maximum sensitivity at 0.508μ. The visibility curve of the average eye [23] (125 observers) is illustrated in curve *C*. Con-

[20] Ives, Astrophys. Jour., **40**, p. 182; 1914. In a recent paper (Astrophys. Jour., **46**, p. 241, 1917) Ives shows that the spectral sensitivity changes with time, becoming relatively more sensitive in the red.

[21] Pohl and Pringsheim, Verh. Phys. Gesell., **15**, p. 111; 1913.

[22] Braun, Dissertation, Bonn; 1906.

[23] This Bulletin, **14**, p. 168; 1917.

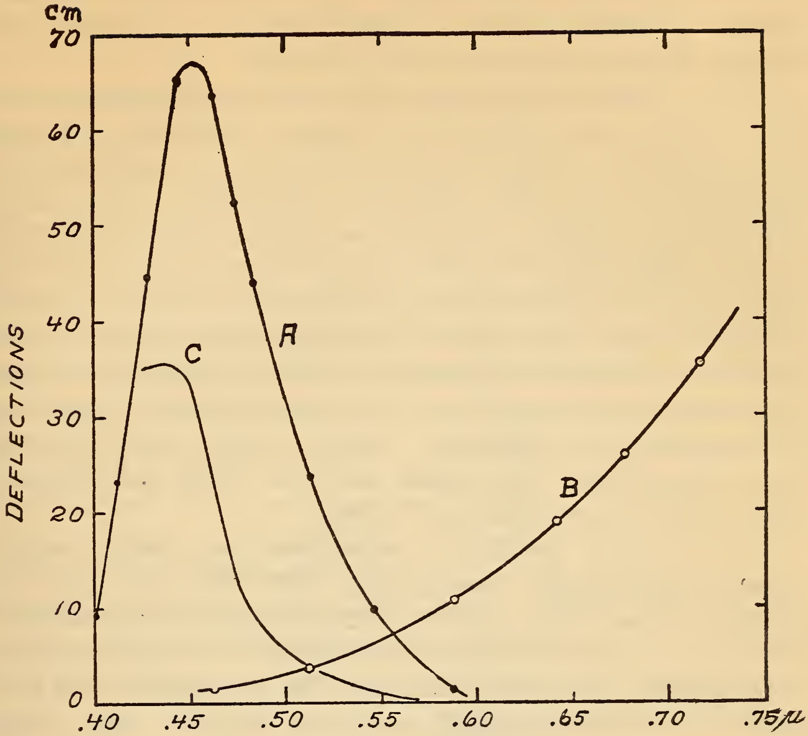

FIG. 3.—*Distribution of energy of a gas-filled tungsten lamp as observed with: A, photoelectric cell; and B, with a thermopile. Curve C is the true sensitivity of the photoelectric cell for an equal energy spectrum*

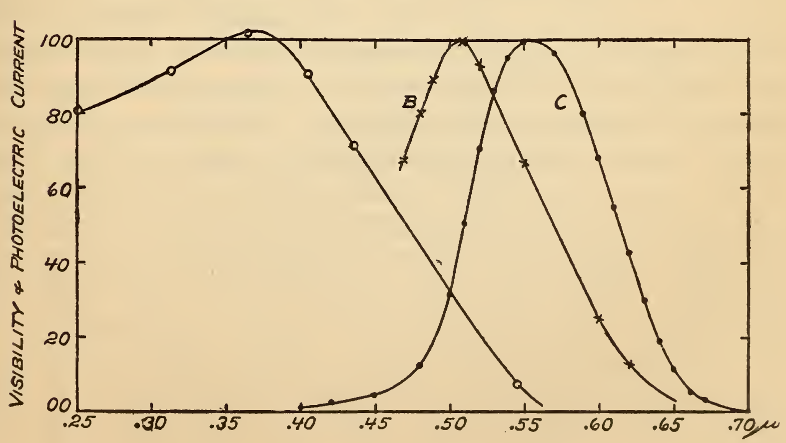

FIG. 4.—*Photoelectric sensitivity: A=calcium; B=rubidium. Sensibility of the average eye: C*

trary to published statements,[24] there is no marked similarity between the photoelectric sensitivity curves of these metals and the wave-length sensibility curve of the eye.

(*f*) *The Auxiliary Galvometer.*—At best a sensitive electrometer is slow to act, and it is difficult to operate, on account of leakage, etc. Attention has already been called [25] to the usefulness of a high-resistance ironclad Thomson galvanometer to measure photoelectric currents. There is, of course, nothing new in the use of a high-resistance galvanometer in a circuit of this type which has a very high external resistance. However, an examination of the older data [26] concerning high-resistance galvanometers (up to 300 000 ohms) shows that the sensitivity obtained is far less than is attainable at the present day, by using even low-resistance galvanometers. During recent years high-resistance galvanometers have been used but little, the Einthoven string galvanometer being used instead.

It is, of course, possible to investigate (and precise work has already been done in investigating) the violet and ultra-violet spectrum by means of a thermopile and a suitable galvanometer. However, it requires an experienced observer to operate this form of radiometer. On the other hand, the photoelectric cell is not affected by thermal changes and stray infra-red rays. Hence, one need not wait until thermal conditions are constant, and the device can be operated by a less experienced observer.

In Fig. 3 is given the distribution of energy in the visible spectrum of a gas-filled tungsten lamp as observed with a photoelectric cell, curve *A*, and with a thermopile, curve *B*. These curves represent actual observations drawn to scale, showing what deflections one would obtain in practice when using these instruments under average conditions. From these curves it is evident that for investigating transmission spectra in the visible and the ultra-violet parts of the spectrum, the most efficient procedure is to use a thermopile for measurements in the red and yellow and a photoelectric cell for measurements in the blue and ultra-violet. The same galvanometer can be used with both instruments. For this purpose an ironclad galvanometer [27] of 20-ohm coils has all its coils joined in parallel (resistance = 5 ohms) when connected with the thermopile, and joined all in series (resistance = 80 ohms) when used with the photoelectric cell.

[24] Ferree and Rand, Psychological Monograph No. 103, p. 45; 1917.
[25] Coblentz, Phys. Rev., **10**, p. 97; 1917.
[26] Ayrton, Mather, and Sumpner, Phil. Mag., **30**, p. 58; 1890.
[27] Coblentz, this Bulletin, **13**, p. 423; 1916.

With such a galvanometer (having its coils all in series) a current sensitivity of $i = 1 \times 10^{-10}$ ampere is easily attained on a single swing of only two seconds.[28] Tests were made upon a two-coil instrument having a total resistance of 1300 ohms. Using a single swing of only two seconds and scale at 2 m the current sensitivity was $i = 2.7 \times 10^{-11}$ ampere. A four-coil instrument, having a total resistance of 5300 ohms and a heavy suspension under similar conditions, had a current sensitivity of $i = 6.2 \times 10^{-11}$ amperes, or 8×10^{-13} ampere for a resistance of 1 ohm.[29]

From this it is evident that a current sensitivity of $i = 1 \times 10^{-12}$ ampere is easily attained, which from personal experience is far greater than will be required for spectral transmission and reflection investigations in the blue, violet, and ultra-violet.

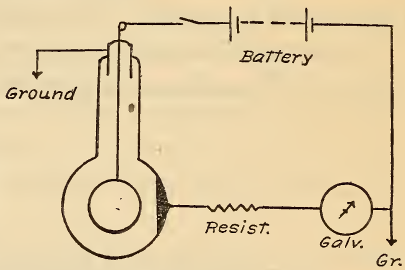

Fig. 5.—*Connections of apparatus when using a galvanometer with a photoelectric cell*

A test was made of the radiation sensitivity of a potassium hydride cell (No. 113, made by Dr. Kunz) when combined with a low-resistance galvanometer (84 ohms) and the above-mentioned high-resistance galvanometer of 5300 ohms. The test showed that when using the high-resistance instrument the radiation sensitivity was at least 10 times as great as when using the low-resistance galvanometer. The computed sensitivity was only 8 times that of the low-resistance galvanometer.

In these tests a 500-watt tungsten stereopticon lamp and also a Nernst glower were used as a source of light. The spectrum was produced by a short-focus, high-intensity illuminator,[30] having a light flint-glass prism and interchangeable plano-convex lenses of quartz and triple achromatic lenses of glass.

The arrangement of the apparatus when using a galvanometer for measuring the photoelectric current is shown in Fig. 5. In order to eliminate leakage currents in the circuit, Nathanson grounded the terminal of the galvanometer which ordinarily would be connected to the negative pole of the battery. The writer did not experience this difficulty when using a galvanometer sensitivity of $i = 1 \times 10^{-10}$ ampere, and hence did not resort to

[28] This applies to a galvanometer which has been in use for two years without remagnetizing the needles. A freshly magnetized suspension would be twice as sensitive.

[29] These coils were wound upon mandrel No. 1, Fig. 1, this Bulletin, 13, p. 426. The coils were wound in two sections of equal resistance, using Nos. 40 and 38 enameled copper wire.

[30] This Bulletin, 7, p. 245, 1911; 13, pp. 358 and 360, 1916.

grounding. However, when using the high-resistance coils the highest current sensitivity would necessitate grounding the instrument.

(*g*) *The Auxiliary Electrometer.*—The electrometer most commonly used with a photoelectric cell is the Dolezalek [31] instrument; Mülly's electrometer [32] has also been used. A new quadrant electrometer by Compton similar to the Dolezalek instrument is just appearing on the market.[33]

In order to shield the electrometer from leakage, static charges, etc., the whole apparatus including the photoelectric cell, is usually inclosed in a tight metal box and the moisture is absorbed by drying material; for example, calcium chloride or better still phosphorus pentoxide. The metal box is grounded.

The needle is usually charged to a potential of 80 to 100 volts.[34] One pair of quadrants is grounded. The other pair of quadrants,

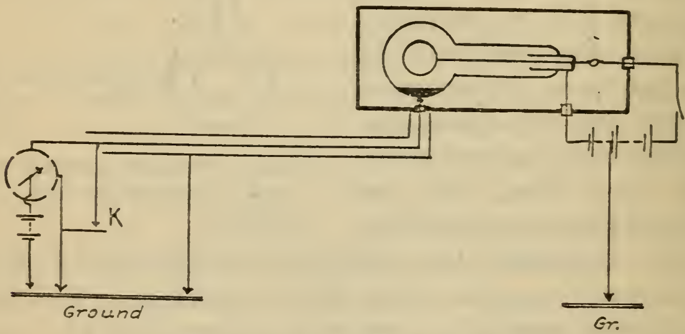

FIG. 6.—*Arrangement of apparatus used by Nathanson*

which can also be grounded, is connected to the cathode of the photoelectric cell.

Nathonson [35] having the electrometer and the photoelectric cell in separate boxes found it necessary to protect the connecting wires, Fig. 6, between these two instruments by passing them through a glass tube which was covered with tin foil and was well grounded. To overcome the drift of the needle of the electrometer

[31] Made by the Cambridge Sci. Inst. Co., Cambridge, England; Dolezalek, Z. S. für Instrumentenkünde 21, p. 345, 1901.

[32] Müll, Phys. Zeitsch., 14, p. 237; 1913.

[33] Compton, Phys. Rev. (2), 7, p. 646; 1916. Made by the Pyroelectric Instrument Co., Trenton, N. J.

[34] The quartz-fiber suspension is from 6 to 9 μ thick; giving a free period of swing of 15 to 20 seconds, and a sensitivity of 300 to 3000 mm per volt difference in potential between the quadrants, depending upon the scale distance.

The quartz fibers are prepared by blowing or shooting (Boys London Electrician, p. 220, Dec. 11, 1896; see also Publication No. 65, p. 70; Carnegie Institution of Washington, 1906). They are rendered conducting by covering them with platinum, deposited by cathode disintegration (Williams, Phys. Rev., 4, p. 517, 914; see also bibliography by Kohlschütter, Jahrb. Radioaktivität, 9, p. 355, 1912.)

[35] Nathonson, Astrophys. Jour., 44, p. 137; 1916.

due to the dark current or leakage current across the glass of the photoelectric cell, he put the metal ring (*B*, Fig. 1) at a potential of about 200 volts below that of the anode. In this manner the drift was completely eliminated.

(*h*) *High Resistance.*—In order to avoid injury to the photoelectric cell by the accidental passage of an excessive current which will result when an excessive voltage is applied to the cell, or when the cell is exposed to light of too great intensity, it is necessary to use a high resistance in series with the galvanometer or electrometer. Various forms of resistances have been used; for example, a solution of mannite with nonpolarizable electrodes,[36] alcohol in a capillary tube,[37] and various forms of carbon resistances.[38] The liquid resistances have not been so satisfactory as is desired, owing to polarization, evaporation, etc. The carbon resistances appear to be satisfactory if care is taken to have good contact at the electrodes. According to Kunz (loc. cit.), when the applied potential difference is greater than 1 volt deviations from Ohm's law are observed.

A carbon resistance is easily prepared by attaching terminals of copper wire, say No. 26, to the ends of a short piece of porcelain tubing (3 cm in length and 3 mm in diameter, such as is used for insulating thermocouples) by melting the wire in a blast lamp. A fine line of graphite (ordinary lead pencil) is then drawn upon the surface of the tube connecting the copper terminals, which are then painted with lampblack in shellac to insure good contact. The resistance is then adjusted by rubbing the pencil line. The whole is then placed in a glass tube about 5 cm long and 8 to 10 mm bore, one end of which is closed with cork, which is perforated to allow the copper-wire terminal to pass through. This tube is filled with melted paraffin and the ends sealed with sealing wax. In most of the resistance units constructed in this manner the resistance increased about four times on applying the molten paraffin. It is, of course, not necessary to embed the resistance in paraffin, but the latter acts as a protection from moisture and mechanical injury. A resistance of one to ten million ohms appears to be the most useful.

(*i*) *Source of Potential.*—A high voltage is easily provided by using a battery of dry cells. The cells used in the smallest flash lamps seem to deteriorate rapidly as a result of corrosion of the

[36] Pohl and Pringsheim, Ber. d. Deutsch Phys. hes., 6, p. 174; 1913.

[37] Nichols and Merritt, Phys. Rev., 34, p. 475; 1902.

[38] Stewart, Phys. Rev., 26, p. 302, 1908; Ives, Astrophys. Jour., 39, p. 428, 1914; Kunz, Astrophys. Jour., 45, p. 69, 1917.

zinc. It is therefore more economical to use the medium-sized cells. These can be arranged in trays or covered boxes and secured by a thin layer of paraffin. They are connected by soldered wires. A battery of 30 cells consisting of 6 rows and 5 cells in a row and giving about 42 volts is a convenient unit to handle. By means of binding posts one can easily arrange to obtain 10 or 20 volts and smaller voltages may be obtained by clamping to the connecting wires.

When the current through the cell increases, there is an appreciable drop in potential at the electrodes of the cell. By means of an additional storage cell and a variable resistance Kunz (loc. cit.) maintained a constant potential as he varied the illumination and hence the current.

(*j*) *Methods of Operation.*—There are several methods for measuring the photoelectric current. In cases where the light intensities are fairly high, the current may be measured directly by means of the deflection of a sensitive galvanometer, provided the question of proportionality is considered. For this purpose the high-resistance ironclad Thomson galvanometer described on page 519 is applicable and is to be recommended.

A second method of operation is to use an electrometer or a sensitive galvanometer as a detector or indicator, and to balance the photoelectric current with a current which can be varied in a known manner."[39]

A third method is to observe the rate of drift of an electrometer needle. Contrary to other observers, Ives[40] found that the needle did not "move at a uniform rate."

A fourth method (which experimenters seem to prefer to the one just described) is the "ballistic throw method." In this method the photoelectric cell is exposed to light for a convenient length of time, say 10 seconds, and the charge acquired by the electrometer needle is noted. The "natural drift" of the needle is determined by noting the drift in 10 seconds when the cell is not exposed to light, and this is subtracted from the observed deflection.[41] To accomplish this, Hulburt broke the ground connection *K*, Fig. 6, and, after conditions had become quiet, recorded the reading of the electrometer needle. He then exposed the cell to light for a definite period, say 10 seconds, and observed the throw of the electrometer needle. This is much quicker than waiting for the steady deflection.

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[39] Griffith, Phil. Mag., **14**, p. 297, 1907; Richtmyer, Phys. Rev., **29**, pp. 71 and 204, 1909.

[40] Ives, Astrophys. Jour., **39**, p. 432; 1914.

[41] Hulburt, Astrophys. Jour., **42**, p. 210; 1915.

Hulburt's grounding key was a pointed brass rod touching a small brass plate, made from the same piece of brass. It gave no trouble with contact difference of potential. Sulphur was used for supporting the wires leading to the electrometer.[42]

Nichols and Merritt [43] have described a method of using the photoelectric cell, whereby the deflection rather than the rate of change of deflection is read. The electrical connections are shown in *A*, Fig. 7. The cathode of the photoelectric cell is connected to one pair of quadrants of an electrometer and also through a resistance, *R* (capillary tube of absolute alcohol with adjustable wire immersion), to earth. The anode (platinum wire) is connected to the plus side of a 110-volt battery. To balance the "dark current" of the cell they connected the other pair of quadrants through a variable resistance to the battery and to earth.

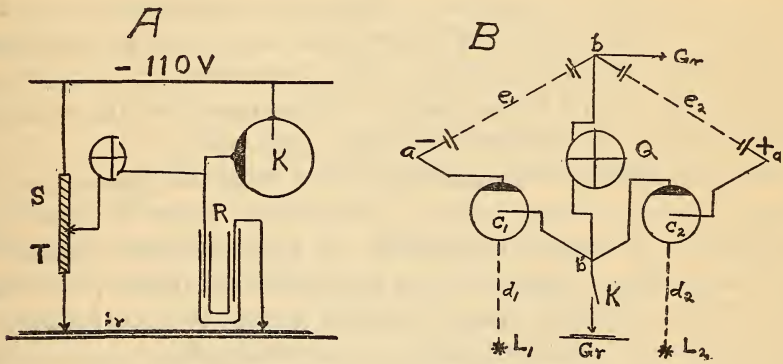

FIG. 7.—*Arrangement of apparatus used by: A=Nichols and Merritt; B=Richtmyer*

By adjusting *S* and *T* the two pairs of quadrants were brought to the same potential when the cell was unilluminated. The deflection of the electrometer upon illuminating the cell was a measure of the intensity of the incident light.

Richtmyer [44] has described a null method of making measurements with photoelectric cells and an electrometer. This evades the question of proportionality of response (photoelectric current) in the cell. The arrangement of the apparatus is shown in *B*, Fig. 7. This requires two photoelectric cells, C_1 and C_2 and two sources of potential, e_1 and e_2, which can be varied from 0 to 120 volts. The minus terminal of e_1 and the plus terminal of e_2 are connected in sort of a Wheatstone Bridge to the photoelectric

[42] For further information concerning keys for connecting and disconnecting the photoelectric cell, the electrometer, and the known emf used for calibration purposes, see McClung, Conductivity of Electricity Through Gases and Radioactivity. See also papers by Cornelius, Phys. Rev., 1, p. 16, 1913, and by Tugman, Astrophys. Jour., 42, p. 321, 1915, for interesting applications of the photoelectric cell.

[43] Nichols and Merritt, Phys. Rev., 34, p. 475; 1912.

[44] Richtmyer, Phys. Rev., 6, p. 66; 1915.

cells. The points b and b' are connected to an electrometer, and are grounded; b' through a suitable make-and-break key, k. By properly choosing the relative values of e_1 and e_2 the dark current through C_1 equals that through C_2, which is determined by the reading of the electrometer when the key k is open.

On illuminating the cells C_1 and C_2 by sources L_1 and L_2 at the distances d_1 and d_2, and adjusting these distances, the photoelectric currents can be made equal, which is indicated by the null reading of the electrometer. For various positions of L_1 there are corresponding positions of L_2 for a balance. By plotting these distances a calibration curve is easily established.

In a recent paper by Kunz [45] various arrangements of apparatus were used. In one case he used an illuminated photoelectric cell as a resistance. The system was found to be very sensitive, but requires great care in handling. In another arrangement, in which the rate of drift method of observation was used, the quadrant electrometer was replaced by a string electrometer in order to eliminate the inertia of the needle. Kunz states that this arrangement seems to be preferred in stellar photometry.

In investigations of transmission and reflection spectra, or in using the photoelectric cell as a photometer, when the source of radiation is of sufficient intensity, an equal-deflection method [46] may be employed instead of the null-deflection method. In this method the radiation passes through a pair of Nicol prisms, a sectored disk of variable opening or an absorption wedge; or the source of radiation is moved upon an optical bench in order to vary the intensity. This intensity is measured after transmission through, or reflection from, the substance under investigation, by noting the galvanometer, or electrometer, deflection. On removing the substance from the path of the rays, the intensity of the direct radiation is reduced, by one of the above-mentioned devices, so that the deflection equals that just observed with the substance in place. The decrease in intensity is easily deduced from the constants of either one of these devices. In this manner the question of the proportionality of the photoelectric current with variation in intensity of illumination is easily evaded. It is easily determined whether the response is directly proportional to the stimulus by using crossed Nicols, a sectored disk,[47] or a plane-parallel plate of colored glass, whose spectral transmission has been determined by a thermopile or some other accurate radiometer.

[45] Kunz, "The law of photoelectric photometry," Astrophy. Jour., 45, p. 69; 1917.

[46] This Bulletin, 12, p. 504; 1916.

[47] Nathanson, Astrophys Jour., 44, p. 137, 1916; Kunz, Astrophys Jour., 45, p. 76, 1917.

After investigating at least a dozen photoelectric cells the writer has come to the conclusion that, if the deflection method is to be used in making the measurements, the proportionality test should be made upon every cell in the apparatus in which it is being used even when the maker's tests indicate that the cell functions in direct proportionality.

For example, a certain potassium-hydride photoelectric cell which was supposed to give direct proportionality was tested by determining the spectral transmission of a certain piece of colored glass by the direct-deflection method. Using a certain intensity of incident light the transmission at a certain wave length was 58.2 per cent. Reducing the intensity of the incident light (gas-filled tungsten lamp, variable current) to about one-half, the transmission was decreased to 55.9 per cent; and on reducing the intensity to one-fourth its initial value, the transmission was reduced to 53.3 per cent. By making corrections for lack of direct proportionality of deflection with intensity of illumination when using this photoelectric cell, the transmission curve so obtained coincided exactly with that observed by means of a thermopile. This cell happened to have a straight line proportionality of current with illumination.

Similar tests were made on other cells, in one of which the current (galvanometer deflection) increased more rapidly than the illumination. Using crossed Nicol prisms and the equal-deflection method, at a certain wave length in the spectrum the rotation of the Nicol prism, N_2[48] (when the test glass was not in the path of the rays), was 50.3°, corresponding to a transmission of 59.2 per cent. The direct-deflection method gave a transmission of 61.7 per cent. When corrected for lack of proportionality of current with illumination, the true transmission is 60 per cent, which is in agreement with the equal-deflection method.

Using another cell, in which the current did not increase as rapidly as the illumination, the apparent transmission of this same piece of glass at the same wave length was 53.2 per cent. Correcting this value for lack of proportionality of deflection (current) with illumination gave a transmission of 59.4 per cent, which is in agreement with the transmission (59.3 per cent) previously observed by the equal-deflection method.

When using such a device as a radiometer by the deflection method, it would evidently be necessary to maintain a constant light intensity and galvanometer sensitivity and calibrate the

[48] This Bulletin, 14 (Fig. 1), p. 173; 1917.

photoelectric cell for lack of proportionality of response with variation in intensity of illumination, such as would be observed in making transmission measurements. In view of the numerous factors that must be taken into consideration in operating a photoelectric cell, the most reliable procedure is to use the null method or the less complicated equal-deflection method just described.

III. THE SELENIUM CELL

The selenium cell is extraordinarily sensitive to light. Unfortunately it has several objectionable characteristics which render it unsuitable for precise quantitative measurements of radiant energy. As will be shown presently, its sensitivity depends upon heat treatment and varies not only with the wave length, but also with the intensity of the light stimulus.[49] In order to use it as a precise radiometer, the sensitivity of the selenium cell must therefore be calibrated for intensity as well as for the wave length of the incident light. This involves comparison measurements with some form of nonselective instrument; for example, a thermopile.

In addition to its variation in sensitivity with intensity and wave length of the stimulus, another objectionable characteristic is its great inertia or slowness to recover its normal "dark" resistance after exposure to light. For example, in experiments made by the writer on various selenium cells obtained in the market (imported and domestic), and also on cells of his own construction,[50] the cell under test was exposed for 5 seconds. After exposure to low intensities it required 30 seconds for a certain cell to recover its normal resistance. Increasing the intensity 20 times as measured with a thermopile the response (galvanometer deflection) as indicated by the selenium cell was only 8 times that of the low intensity, while the delay (2 minutes) in recovery to normal resistance was increased 4 times. Exposure to daylight required more than 10 minutes for recovery.

Hence, if an attempt is made to use the selenium cell as a photometer, it must be operated in a special manner as regards intensity, time of exposure,[51] etc.

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[49] The literature bearing upon this subject is very extensive, and handbooks have been written on it, e. g., C. Ries; "Electrical properties of selenium." Also "Das licht in seiner elektrischen und magnetischen wirkungen, Leipzig, 1909." See also papers by Pfund, Phys. Rev., 28, p. 324, 1909, and by Brown and Sieg, Phys. Rev. (2), 2, p. 487, 1913; (2), 4, p. 48, 1914.

[50] Two of these cells were made nine years ago.

[51] Pfund, Phys. Rev., 34, p. 370; 1912.

The single crystals of selenium grown by Brown [52] have an extraordinarily high sensitivity as compared with a selenium cell; but they also have the characteristic slow recovery after exposure to light. From published data it appears that a single crystal of selenium, 1 mm² in area, is 100 times as sensitive as the best selenium cell. In connection with a 36-inch telescope such a crystal receiver could detect the light from a candle at a distance of 350 miles.

The wave-length sensitivity curve of a selenium crystal depends upon the temperature at which the crystal was formed. A crystal which was formed in the cooler part of the furnace had its maximum sensitivity in the violet.[53] A crystal formed in the hottest part of the furnace had its maximum sensitivity in the extreme red, just as is true of an ordinary selenium cell which is, no doubt, composed of mixed crystals.

Brown [54] and his collaborators have recorded many types of sensitivity curves, and Dietrich,[55] has shown that the character of the wave-length sensitivity curve of selenium can be controlled by heat treatment. Annealing the cell at 200° C. produces a maximum sensitivity in the extreme red, while annealing at 150° C. shifts the maximum sensitivity to 0.55μ.

From the foregoing brief summary of experimental data now available it appears that selenium as such does not have a characteristic wave-length sensitivity curve; that the magnitude and position of the maximum of sensitivity in the spectrum can be controlled by heat treatment of the selenium.

It is of interest to compare the distribution of energy in the visible spectrum of the Nernst glower as registered by means of a selenium cell and by a thermopile. The former was used in connection with a d'Arsonval galvanometer and the latter with a Thomson galvanometer. Fig. 8, curve *A*, gives the spectral energy distribution obtained with a bismuth-silver thermopile (a nonselective radiometer), while curve *B* gives the response of a selenium cell when similarly exposed (for 10 seconds) in different parts of the spectrum. After exposure to the low intensities, in the blue violet, it requires 20 to 30 seconds for the galvanometer reading to return to zero; and after exposure to the highest inten-

[52] Brown, Phys. Rev. (2), 4, p. 85, 1914; Electrical Experimenter, 3, p. 677, 1916. In the present investigation two cells of single crystals were tested.

[53] See further data by Sieg and Brown, Phys. Rev. (2), 5, p. 65; 1915.

[54] Brown and Sieg, Phys. Rev. (2), 4, p. 48; 1914.

[55] Dietrich, Phys. Rev. (2), 4, p. 467, 1914; 8, p. 191, 1916.

sities it required over 2 minutes for the cell to return to its initial resistance.

The curve obtained with the selenium cell is entirely erroneous as regards the actual spectral energy distribution. Similarly, erroneous results would be obtained if one attempted to measure the radiation from red and from blue stars.

Curve *C* gives [56] the response that is obtained by exposing the selenium cell to equal amounts of energy in different parts of the spectrum using a high intensity, while curve *D* represents the response at one-sixteenth the intensity used to obtain curve *C*. According to the measurements of Pfund, for wave lengths shorter than 0.65μ the deflections of the galvanometer (used in connection with the selenium cell) are approximately proportional to the square root of the incident energy, while for wave lengths greater than 0.7μ the deflections are approximately directly proportional to the intensity of the incident light. (Exposures were 12.5 seconds.)

The present discussion of selenium as a radiometer relates to the application of the device as a high-precision instrument. In view of the adverse facts just reported it is but fair to add that the device is very sensitive, and in the early work on the photometry of variable stars some far-reaching results have been obtained by Stebbins.[57] He recognizes, however, that the photoelectric cell (of rubidium which from tests made in this laboratory is only one-sixth as sensitive as potassium hydride) is five to six times as sensitive as the selenium cell.[58]

It is relevant to add that, concerning the peculiar electrical properties of selenium, some hold the view that the increased conductivity of selenium is caused by (a resonance) freeing of electrons on exposure to light. Others consider it a modification of the crystal structure, assuming that selenium occurs in several allotropic forms of widely different electrical conductivity. The absence of polarization indicates that the conduction is not electrolytic. Experiments at liquid-air temperatures, where the light sensitivity is retained, seem to be evidence supporting the electronic hypothesis.[59]

In conclusion it may be added that the selenium cell may be used as an indicator in the null and the equal-deflection methods of obtaining ratios of intensities which were considered in the

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[56] Pfund, Phys. Rev., 34, p. 370; 1912.
[57] Stebbins, Astrophys. Jour., 39, p. 459, 1914; 42, p. 133, 1915.
[58] Stebbins, Observatory, No. 501, p. 257; 1916.
[59] Elliot, Phys. Rev. (2), 5, p. 53; 1915.

operation of the photoelectric cell. For example, the galvanometer deflection might be observed when the cell is exposed for, say, five seconds to the lower intensity. Then the higher intensity is reduced, by means of (calibrated) crossed Nicol prisms, a wire grating, an absorption wedge, a variable-sector disk, or some

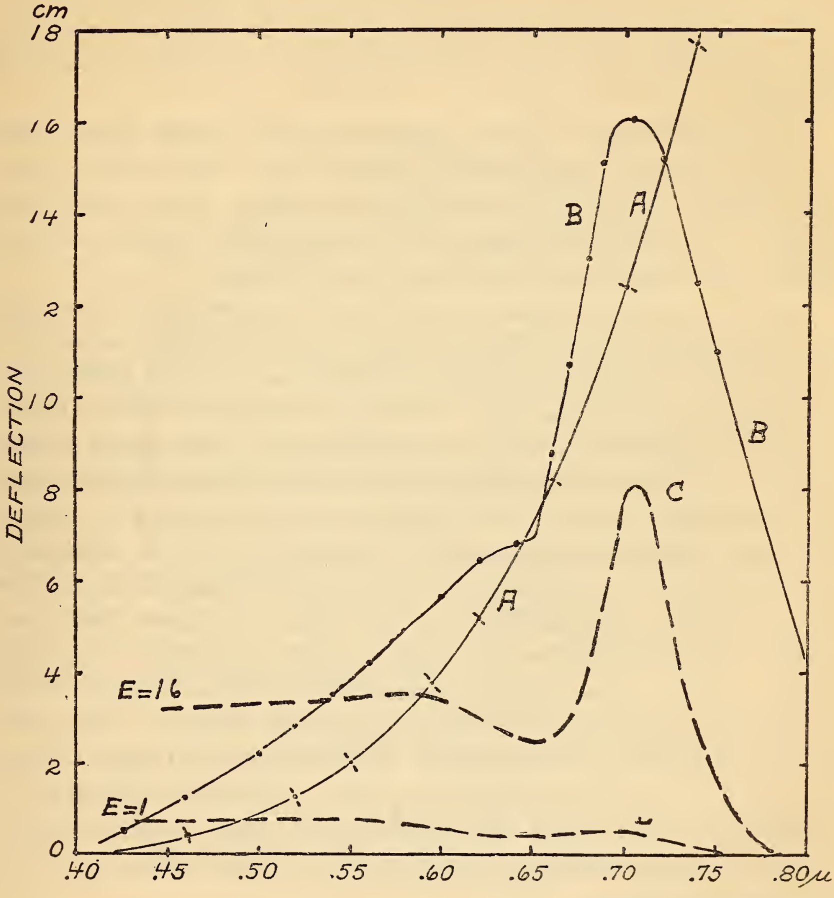

FIG. 8.—*Distribution of energy in the spectrum of a Nernst glower as observed with a nonselective radiometer, A, and with a selenium cell, B. Curves C and D (from Pfund) give the responses of a selenium cell in an equal energy spectrum*

other device, to give the same deflection. In this manner the ratios of intensities of monochromatic light of the same wave length might be observed; but the selenium cell can not be used in this manner to compare accurately the intensities of light of two sources differing in color. This restriction applies, of course, to all of the instruments discussed in this paper.

IV. PHOTOGRAPHIC RADIOMETRY

The use of the photographic plate is a roundabout method for making radiometric measurements. It has been used in measuring the distribution of energy in the spectrum of the light of the firefly,[60] and, more recently, in the determination of stellar magnitudes.[61] In the latter method the blackening of the photographic plate by the star images is measured by photometering the plate by means of a bismuth-silver thermopile of special design.[62]

Probably the most useful application of the photographic plate is in determining transmission spectra in the ultra-violet part of the spectrum, especially of substances having sharp absorption bands. Various arrangements of apparatus and methods of exposure have been used,[63] the most recent being by Howe.[64]

In view of the fact that so much can be accomplished by using the photoelectric cell, which is rapidly approaching perfection as a radiometer, it seems unnecessary to fully discuss the applicability of photographic radiometry. It may be added, however, that a series of exposures can be quickly made upon a photographic plate and in this manner a permanent record obtained of transmission and reflection spectra. The plates can be examined at leisure. By using spectral lines the effect of diffuse light can be eliminated by comparing the image of the line with the effect of the diffuse light upon the adjacent part of the plate. A plate holder is a rather simple instrument as compared with a photoelectric installation, and it remains to be determined whether the latter will prove more accurate than the photographic method. One criticism that has been made against the photographic method is that the plate is not very sensitive to small variations in intensity, so that in the "flat" part of a transmission curve great variations occur in the photometric observations of the blackening of the photographic plate.

V. SUMMARY

The present paper deals with the application of certain special physical and chemical properties of matter as a means of quantitatively measuring radiant energy.

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[60] Ives and Coblentz, this Bulletin, 6, p. 321, 1909; Coblentz, Publication No. 164, Carnegie Institution of Washington, 1912.

[61] Stetson, Astrophys. Jour., 43, pp. 253 and 325; 1916.

[62] This Bulletin, 11, p. 168; 1915.

[63] Ham, Fehr, and Bitner, Jour. Franklin Inst., 178, p. 299; 1914.

[64] Howe, Phys. Rev. (2), 8, p. 674; 1916.

Certain substances have the property of decreasing in electrical resistance when exposed to radiant energy of short wave lengths, especially the visible and ultra-violet rays. Crystalline selenium belongs to this class of substances, and because of its very marked response to light, its application as a radiometer has been thoroughly investigated by many observers. The sensitivity of the selenium cell varies not only with the wave length but also with the intensity of the light stimulus, and it recovers but slowly from the effects of the light stimulus. It therefore fails to meet the requirements of a radiometer, except that of high sensitivity.

The application of the photochemical action upon a photographic plate, as a means of making quantitative radiometric measurements, is considered. While this method of radiometry has been used successfully, its applications seem to be rather limited.

A third application to radiometry considered in this paper is based upon the fact that some substances, when charged to a negative potential, lose their charge when exposed to light, especially violet and ultra-violet rays. In this respect the alkali metals, and especially their hydrides, are very sensitive to light stimuli. The photoelectric cells made of these substances can be constructed and operated so that the response (photoelectric current) is directly proportional to the intensity of the stimulus. This meets one of the principal requirements of a satisfactory radiometer. Details of the construction, operation, and characteristics of the photoelectric cell are given.

Attention is called to the importance of making the proportionality test of the photoelectric outfit as used, especially of cells with spherical bulbs.

A satisfactory, high-resistance, ironclad Thomson galvanometer is described which may be used successfully with the photoelectric cell.

The advantages of the photoelectric cell over the thermopile are considered and the application of the former is suggested for measurements of radiant energy (especially ratios of intensities) in the violet and ultra-violet parts of the spectrum, where the photoelectric cell greatly exceeds the thermopile and the bolometer in sensitivity.

In conclusion, special acknowledgement is due W. B. Emerson for assistance in this investigation.

WASHINGTON, September 10, 1917.

APPENDIXES

Appendix 1.—NEW DESIGNS OF RADIOMETERS

In continuing the improvement of stellar radiometers several new designs of instruments were considered and some of the preliminary tests of their efficiency appear to be of sufficient importance to warrant publication.

When a very thin strip of blackened metal—for example, a bolometer strip—is exposed to radiation it becomes warmed and it, in turn, emits radiation. In previous investigations of the diffuse reflecting power of various substances [65] and of the behavior of an absolute thermopile,[66] it was found that this warming of the receiver is quite appreciable, and that this receiver can be a very efficient secondary source of radiation which, in turn, can be used to stimulate a radiometer. The utilization of this secondary source of radiation can be accomplished by placing the receiver at the center of an accurately ground hollow sphere having an opening to admit radiation. In this case one would utilize the "reradiation" which has to be very carefully excluded in diffuse-reflection measurements.[67]

One method of increasing the radiation sensitivity of a bolometer is to place a plane—or cylindrical mirror close back of it, to reflect the radiation emitted by the bolometer strip back upon itself.

Another method for utilizing this radiation is by the employment of multiple receivers, one being placed back of another; for example, a thermopile receiver back of a bolometer strip, or one bolometer strip or thermopile receiver back of another. It is with this method that the present paper is chiefly concerned.

The efficiency of such a device was tested in the following manner. Two strips of very thin platinum, such as is used in bolometers (thickness about 0.0008 mm), about 6 by 20 mm in area were mounted over slits cut in cardboard which was 0.45 mm thick. Both sides of these strips were painted with a thin coat of lampblack and covered with soot from a sperm candle. The thermopile receiver was 1.8 by 16 mm. Slits of bright aluminum 0.85 mm thick were placed in front of the thermopile or in front of the blackened platinum strips when they were in front of the thermopile. The distance between the thermopile receiver and the platinum strip (and between the two platinum strips) was 0.45 mm. When the thermopile was exposed directly to a standard of radiation the deflection was 12.15 cm; when one platinum strip intervened the deflection was 5.88 cm; and when the two platinum strips were in front of the thermopile the deflection was 3.57 cm.

The Multiple-Bolometer Receiver.—Since there is but little difference between the radiation sensitivity of a bismuth-silver thermopile and a bolometer, the above tests show that the radiation sensitivity of a bolometer can be increased by 50 per cent by having the receiver (the arm of the bridge) consist of two strips, one back of the other,

[65] This Bulletin, **9**, p. 283; 1913.

[66] This Bulletin, **11**, p. 157; 1914.

[67] Paschen (Ber. Berliner Akad., p. 409; 1899) appears to be the first to use a hemispherical mirror in front of a bolometer in order to "blacken" it. The device has been used extensively by the writer (this Bulletin, **4**, p. 392; 1908). In spectral-radiation work care must be exercised to avoid reflection of radiation from the adjacent parts of the spectrum upon the bolometer strip. In investigations where it is unimportant whether some of the incident beam of radiation falls upon a reflecting surface at the rear of the receiver before it falls upon the receiver—that is, in cases where it is unimportant whether the complete beam of incident radiation is completely intercepted by the receiver—it is possible to place the receiver at the center of an accurately made hollow sphere as just mentioned. Pfund (Phys. Rev., **34**, p. 288; 1912) claims a very large increase in sensitivity as the result of using a thermojunction at the focus of a spherical mirror.

the front strip being exposed to radiation; and instead of a galvanometer deflection of 12.15 cm, as just noted, the total deflection would be (12.15+5.88=) 18 cm. By using three strips placed one back of another the galvanometer deflection would be increased by about 80 per cent (21.6 cm as noted above) and by using four strips (joined in series, or a single strip folded three times) the deflection will be double that produced by the front strip. The sensitivity of the whole combination would be further increased by placing this multiple receiver at the focus of a hemispherical mirror.

The Bolo-Pile.—This is a combination of a single bolometer strip, close to the back of which is placed the receiver of a thermopile. The latter is so constructed that the pairs of receivers are in two rows corresponding to the two bolometer strips. In this manner the heating produced by the current passing through the bolometer strips will produce no deflection in the thermopile circuit. The manner of connecting the bolometer and the thermopile circuit to the galvanometer will depend upon the relative change in voltage of the two circuits when the receiver is exposed to radiation. If the error due to shunting is too great when the two circuits are joined to the same binding posts, the bolometer current can be passed through one galvanometer coil and the thermopile current through another coil.

The simplest and probably the most useful arrangement is a bolometer consisting of two branches of thin narrow strips of platinum close back of which is placed a thermocouple. In measuring the heat from stars a gain in sensitivity as low as 50 per cent in sensitivity is worth considering.

The Multiple-Thermocouple Receiver.—The use of two thermocouples, joined in series, with the receivers one back of the other, has not yet proved to be so efficient, because of the greater heat capacity of the thermocouple receiver used as compared with a bolometer. The comparison of this combination with the two preceding instruments, and with a single thermocouple (or bolometer) in the focus of a spherical inclosure, in which all the parts are reduced to the dimensions which would be used in measuring stellar radiations, is in progress.

In conclusion it may be added that as a result of the writer's previous measurements of stellar radiation [68] the conclusion was reached that, in order to do much successful work in stellar radiometry, it will be necessary to have a hundred-fold greater sensitivity than that previously employed. This gain in sensitivity was to be attained by increasing the light-gathering power of the telescope five times, the sensitivity of the galvanometer ten times, and the radiometer sensitivity two times. In a paper [69] just published data are given showing an increase of more than ten times in the galvanometer sensitivity, while the present paper indicates the way to double the radiometer sensitivity. Apparently, then, it remains to find a suitable mirror and funds to operate it.

With the thermocouple and 36-inch reflector used by the writer in 1914, it was possible to measure the radiation from a seventh-magnitude star. The sensitivity was such that a 1-mm deflection would have resulted from sighting a 36-inch telescope upon a candle placed at a distance of 53 miles.

As just mentioned, the sensitivity of the radiometric outfit, alone, can now be increased more than twenty times, so that a 1-mm deflection would be produced by a candle at 240 miles. Or reading to 0.2 mm this means that one can *detect* the total radiation from a candle at 500 miles, using a 3-foot reflecting telescope; or, using a 6-foot reflecting telescope, thus gaining four times in light-gathering power, this means that one can *detect* a candle at a distance of 1000 miles. This is on the basis of a galvanometer sensitivity of $i=1\times10^{-11}$ amperes, which is easily attained. The main difficulty will arise in obtaining steady conditions. The modern observatory, with its complicated electrical machinery and power plant, is not the ideal place one might imagine it to be for making delicate radiometric observations.

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[68] This Bulletin, 11, p. 613; 1914.

[69] This Bulletin, 13, p. 423; 1916.

Appendix 2.—AMPLIFICATION OF THE BOLOMETER CURRENT

The electric current obtained from radiometrically heating a bolometer receiver is exceedingly small. In the foregoing appendix methods are described for increasing this current.

Another method for increasing the response of a bolometer is by amplifying the the electric current which would ordinarily pass through the galvanometer by passing it through an audion amplifier. In the present experiments the receiver consisted simply of a thin blackened strip of platinum or gold leaf (and a storage battery), which were suitably connected into the grid circuit of a three-stage audion amplifier. A telephone receiver was connected in the usual manner to the amplifier.

The source of radiation was an acetylene flame. The receiver was exposed to this flame through a rotating sectored disk having 15 openings. This combination formed a radiophone.

When a sensitive platinum bolometer receiver was used as a radiophone, the sound produced in the telephone was not very audible. This is no doubt attributable to the great heat capacity of the material, which prevented the rapid changes in resistance and hence in electric current form being of sufficient magnitude to affect the telephone receiver.

Using a lightly smoked strip (6 by 2.5 mm) of gold leaf, the ends of which were clamped between thin (0.02 mm) strips of tin, the sound produced in the telephone receiver was as loud as was observed in a photophone made of selenium.[70] This device was mounted in a glass bulb, which could be evacuated. As was to be expected, there was no marked difference in the intensity of the sound produced when operated in air and in a vacuum.

In the gold-leaf radiophone, as used, the limit of audibility was attained for a light (radiant power) intensity of 4.8×10^{-5} watts. Using a larger receiver and amplifier, and a larger current (which was 0.2 ampere in the present tests) through the receiver, the sensitivity could be greatly increased.

Appendix 3.—ELIMINATION OF SCATTERED RADIATIONS IN SPECTRAL-ENERGY MEASUREMENTS

For completeness of discussion of the subject of methods of radiometry, as well as for the reason that, among experimenters, especially beginners in spectroradiometric work, the importance of eliminating scattered radiations in emission, reflection, and transmission measurements is not fully realized, it is relevant to discuss this topic.

One method of reducing the intensity of the scattered radiations of various wave lengths from the energy measurements at a given point in the spectrum is to operate two spectroscopes in series. This is most useful in spectral energy measurements, e. g., in the spectrum of a black body. This method has been used by Langley in his measurements of the spectral radiaton from the moon, and also by Paschen in some of his determinations of the constant of spectral radiation.

In the measurement of the spectral reflection from, or transmission through, various substances, a simpler procedure is to use screens which are opaque to most of the radiations excepting the spectral region in which measurements are to be made. In view of the fact that in transmission or reflection measurements the ratio of two intensities is desired and not the absolute intensity of the source it is unnecessary to know the exact transmission of the screen at the point in the spectrum at which measurements are being made.

In visual work (spectrophotometry) it is necessary to eliminate simply the scattered rays which affect the eye by placing gelatin films stained with dyes,[71] or colored

[70] Jour. Wash. Acad. Sci., 7, p. 525, 1917; this Bulletin, 14, p. 591, 1918.

[71] Uhler and Wood, Atlas of Absorption Spectra, Publication No. 71, Carnegie Institution of Washington, 1907.

glasses in the path of the rays. When using a selective radiometer (e. g., a photo-electric cell) which does not respond to infra-red rays it is not necessary to eliminate these rays scattered over the visible and ultra-violet part of the spectrum.

When spectral energy measurements are made in the visible and ultra-violet by means of a thermopile or bolometer, the infra-red rays can be eliminated by placing before the spectrometer slit a weak solution of cupric chloride [72] or a glass which is opaque to infra-red rays.[73]

A further device is a shutter which is opaque to the radiations in that part of the spectrum which is under investigation, but which is transparent to the scattered rays. This procedure is particularly valuable in spectral energy measurements. In his infra-red investigations Rubens used shutters of quartz, fluorite, and rock salt which are as opaque as a metal shutter for wave lengths which are greater, respectively, than 8μ, 12μ, and 30μ, but which are transparent for radiations which are less than 4μ, 7μ, and 12μ, respectively. The scattered radiations which are transmitted by these shutters impinge upon the radiometer practically with the same intensity, whether or not the shutter is in place before the spectiometer slit and hence do not affect the energy measurements.

For spectroradiometric measurements in the yellow to the violet, a shutter of Corning red glass and in the ultra-violet a shutter of amber (or Crooke's neutral tint) glass should be used. Clear glass and mica are opaque to rays less than 0.3μ. These glasses are very transparent to part of the visible and the infra-red rays and they are opaque for radiations of wave lengths less than 0.58μ and 0.4μ, respectively.[74]

The use of rough surfaces which scatter the short wave-length radiations and specularly reflect the long wave-length radiations is a further method for investigating the extreme infra-red, which is suggested by the investigations of Gorton.[75]

Appendix 4.—USE OF A ROTATING SECTORED DISK IN RADIOMETRY

In photometric and radiometric measurements involving high intensities a common practice is to reduce the incident radiations by means of a rotating sectored disk.

In photometry it is well established [76] that the response of the eye is of such a nature that, physiologically as well as physically, a rotating sectored disk transmits light proportional to the angular openings in the disk.

Recently Kunz [77] has shown that the photoelectric cell functions so as to indicate that the light transmitted by a rotating sectored disk is proportional to the mechanically measured apertures; that is, Talbot's law holds for the photoelectric cell.

Some years ago the applicability of the rotating sector disk for reducing the intensity of the energy incident upon a bolometer was tested by the writer, who found [78] that the energy transmitted is appreciably greater than the theoretical value; that is, the value indicated by the mechanical measurement of the openings in the disk. Extensive experimental data were obtained showing that this increased radiation through the openings was a function of the speed of the disk and to some extent a function of the distance intervening between the disk and a screen which faced the bolometer. The explanation offered was that diffraction of the rays of great wave length produced an apparent aperture which was larger than the mechanically measured opening in the disk. This explanation does not, however, fully explain the obseravtions when the distance was varied between the disk and the screen diaphragm.

[72] This Bulletin, 14, p. 229; 1917. For investigating the extreme infra-red solar spectrum, Fowle, Smithsonian Miscell. Coll., vol. 68, No. 8, 1917, used an absorption screen of solid iodine.

[73] See Technologic Paper No. 93, issued by this Bureau.

[74] Coblentz and Emerson, Technologic Paper No. 93, this Bureau; Luckiesh, Trans. Illum. Eng. Soc., p. 472, 1914; Bell, Proc. Amer. Acad. Arts and Sci., 46, p. 669, 1911.

[75] Gorton, Phys. Rev. (2), 7, p. 66; 1916.

[76] Hyde, this Bulletin, 2, p. 1; 1906.

[77] Kunz, Astrophys. Jour., 45, p. 69; 1917.

[78] This Bulletin, 4, p. 455; 1907.

These observations were so novel at the time that part of the manuscript was not published. The published data brought forth communications from observers who had not found this discrepancy in their work. This difference in observations has remained unsettled until recently, when Fowle[79] published a verification of the writer's observations, showing that the energy transmitted by a rotating sector is always greater than the theoretical value. For instance, his 0.333 sector had an aperture of 0.344 as determined radiometrically.

From these experiments it is evident that the rotating sectored disk can not be used for reducing intensities in radiometric work unless the disk is mounted close to a stationary diaphragm and operated[80] at a slow speed as described in the writer's original communication.

In a recent investigation Mendenhall[81] employed a rotating sector disk and thermopile in determining the constant of spectral radiation. Aside from the temperature scale used (m. p. of Pd. 1549 instead of 1555° C), recently adopted by experimenters, it would be of interest to know whether the rotating sectored disk contributed to the production of a high value ($C_2 = 14\,400$) of this constant.

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[79] Fowle, Smithsonian Miscell. Coll., **68**, No. 8, p. 14; 1917.

[80] This Bulletin, **7**, p. 249; 1911.

[81] Mendenhall, Phys. Rev. (2), **10**, p. 515; 1917.